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Advanced analysis of laser beam polishing of quartz glass surfaces

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Abstract

The laser beam is a small, flexible and fast polishing tool. With laser radiation it is possible to finish many outlines or geometries on quartz glass surfaces in the shortest possible time. It’s a fact that the temperature developing while polishing determines the reachable surface smoothing and, as a negative result, causes material tensions.
To find out which parameters are important for the laser polishing process and the surface roughness respectively and to estimate material tensions, temperature simulations and extensive polishing experiments took place. During these experiments starting and machining parameters were changed and temperatures were measured contact-free. The accuracy of thermal and mechanical simulation was improved in the case of advanced FE-analysis.

Keywords: laser; contactless measurement; quartz glass; polishing; temperature; residual stress; simulation; sensitivity

1. 1. Motivation / State of the Art

The methods of polishing surfaces with laser radiation are documented in the literature. It’s possible to reduce polishing time of metallic injection molding molds from 30min/cm² to a few seconds per cm². The laser material processing of glass has made good progress whereas the high-precision finish (for optical parts) causes still problems. It’s barely possible to reach good surface quality without creating thermal tensions. To finish the quartz glass parts in this report a CO_2-laser is used. The analysis should show how the starting roughness, the laser parameters and the resulting temperature influence the final surface quality. It’s interesting too, how the parameters have to be changed to reach requested roughness values.

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The optimization of the process parameters should be carried out by measuring temperature and surface quality. This quality is detected by the help of different surface analyzing methods.

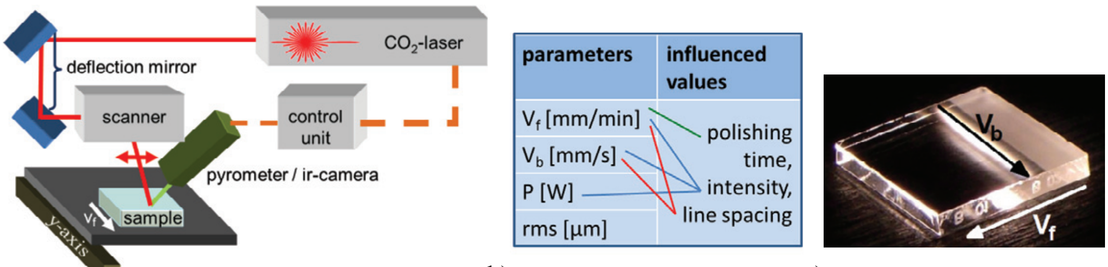
2. Concept of Laser-Beam-Polishing (LBP)

A 1.5 kW CO_2-Laser (10.6 µm) with a high rate of absorption in quartz glass is used to soften the surface by inserting energy. Because of material tensions in the softened surface layer unevenness and roughness are smoothed. This polishing process could cause stock removal (sublimation) too, so it is necessary to determine an appropriate temperature range for polishing without it.

The experimental setup shown in Fig. 1 consists of a CO_2-laser beam coupled in a portal system, guided over several mirrors to a scanner (maximum scanning velocity 3 m/s). The feed-rate is realized by the portal system. Thus the motion forms a 'laser line' that moves along the surface. The applied measurement system to detect the temperature distribution as an essential determining factor is realized by a pyrometer (5.14 µm), whose measuring spot is located in the middle of the 'laser line' for constant temperature recording by moving with the line in means of process optimization. The maximum temperature and a temperature curve for each polished sample are recorded. They can be used to check the influence of the machining parameters on temperature and furthermore the influence of the temperature on the reachable surface quality. An additional IR-camera is applied in the course of the later tests to confirm the pyrometric measurement results and the supposed temperature distribution.

3. Experiments

The polishing is carried out by a regional short melting of a thin surface layer with a defocused beam. Using adjusted laser power stock removal is prevented and the smoothing happens because the surface tension of the melting layer. This tension is responsible that the profile peaks were leveled and the valleys were filled.



a) b) c)

Fig. 1. (a) scheme of experimental setup; (b) range of polishing parameters; quartz glass sample during the polishing process

Because of this high velocity a polishing line (Fig. 1 c) is generated on the glass part (part size: 25 x 25 x 4 mm³). The feed rate v_f is realized with the axis of the portal system. The pyrometer measuring spot for the temperature recording is carried within the polishing line. The measuring system detects the surface temperature (T) and the developing T curve is used to optimize the process parameters (shown in Fig. 1 b). A DoE with a 2^3 experimental design (one center point, one repetition) regards the influence of the parameters with developing temperature, roughness (RMS) and stock removal (SR) as investigated role variables. Table 1 shows the range of parameter-variation.

Table 1. range of parameter-variation

v_b [mm/s]	v_f [mm/min]	P [W]	RMS [µm]
600 …1500	12 … 50	490 … 1000	0,2 … 0,8

Parameter estimates based on student's distribution (t) show the significance of the effects given by P, v_f, v_b and their combination. The red lines in Fig. 2 are the confidence regions. Confidence regions are an effect or a combination of effects cross the 99.9 % - line it counts as highly significant. If it stays under the 95 % - line it is not significant. It is consequential to set these parameters on an average value and reduce the following experimental amount that way. Significant influences on role values RMS, SR and T are P, v_f and their combinations. The simplification of a "polishing line" is feasible because v_b shows no significance. The enormous influence of T and the interaction between temperature and surface quality was examined intensively thus an ideal temperature range to finish rough-machined quartz glass surfaces in just one laser-polishing step without significant stock removal is set.

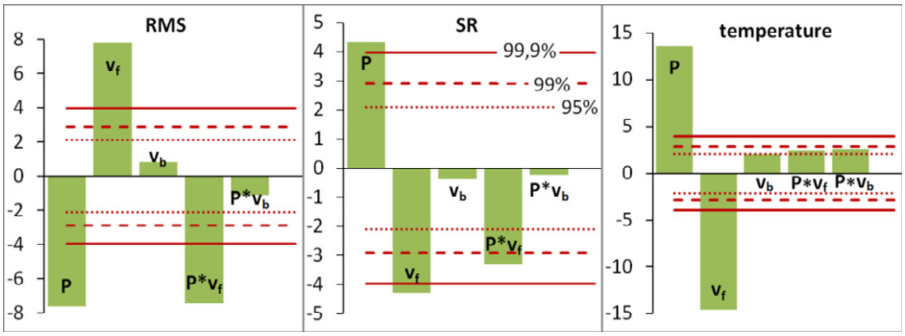


Fig. 2. effects significance test of RMS, SR and temperature

As predicted, the results of the DoE show the enormous influence of the temperature, as well as the interaction between temperature and surface quality - demonstrated in Fig. 3 a. There is indeed an ideal temperature range (marked in Fig. 2 a) wherein it is possible to finish rough-machined quartz glass surfaces in just one laser-polishing step – without significant stock removal. The heat image in Fig. 3 b emphasizes the heat distribution on the quartz glass surface and – regarding the front side – in the surface. It can be seen, that the assumed laser line (caused by the rapid beam moving) is actually developing during the polishing process. This relatively broad area assures the evenly surface melting that is required to reach the high surface quality of 10 nm (rms) and less.

Concerning surface quality it turned out, that a clean surface is required. Analyses with a scanning electron microscope (SEM) show micro-defects and enclosures on the polished surfaces. Theses impurities are elements of pre-machining agents (lapping suspension, tool abrasion) located in/on the glass surface structure or fine parts (dust) from the polishing environment. If these parts stay or fall on the softened surface they create a new glass blend with a different coefficient of expansion. In the worst case tension increases during the fast cooling and the glass blend breaks away. SEM-pictures of a quartz glass surface before and after polishing demonstrate the described effect.

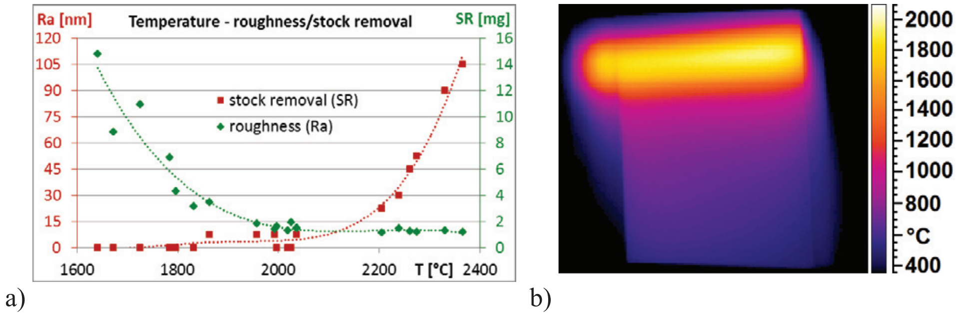


Fig. 3. (a) interaction between temperature and surface quality/stock removal; (b) heat image of a polished quartz glass sample

The mechanical properties of a laser polished surface were also examined during these researches. When creating a juvenile surface it turned out, that the bending strength increases with laser polishing. The micro hardness is comparable to a mechanically polished surface but there is no soft gel layer that normally causes a hardness depending upon depth.

4. Simulations

The numerical simulation allows the thermal and mechanical analysis of the polishing process to determine the temperature state and stress state during the process and to optimize the process parameters. The numeric simulation uses a three-dimensional model, which also includes physical non-linearity in the decoupled thermal and mechanical simulation. In the first step, it is important to describe the energy input. The wavelength of a CO_2-laser beam is $\lambda = 10.6$ µm. In the infrared range above the wavelength of five µm silicate glasses are nearly opaque. For an absorption coefficient of $\beta = 10^3$ cm^{-1} the optical penetration is less than 10 µm. The radiation intensity of the laser without optical correction is assumed idealized mathematical GAUSSian distributed in the simulation. It is created two energy distributions for the moving laser (heat input model 1) and implemented in the numerical model. The first equation describes energy input depend on time and position. It was assumed that the laser beam across the sample surface sufficiently quickly and heat up the sample equal. The second description of the laser beam is a moving source. The very high speed of the laser beam on the sample surface is considered in the equation for the position determination of energy input:

$$x(t) = \frac{b}{\pi}\left(\frac{\pi}{2} - \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{\cos\left((2n-1)\frac{t}{a}\right)}{(2n-1)^2}\right) - \frac{b}{2} \quad (1)$$

with a - function for time alignment, b - function for amplitude, corresponds to 1.05*sample width, t - time. The energy input is described with equation (heat input model 2) depend on time and position:

$$q(x,y,z,t) = h(t)Pe^{\left(-\frac{(x-x(t))^2}{A^2}\right)}e^{\left(-\frac{(y-y_0-v_f t)^2}{A^2}\right)}e^{\left(-\frac{(z-z_0)^2}{B^2}\right)} \quad (2)$$

with h(t) - function for mesh of the model and the position of the heat source, P - heat input or power, x(t) - function of position, y_0, z_0 - start-position in y- and z-axes of the heat source, x,y,z - x-, y- and z-position of a node, v_f - feed rate of polishing line, t - time, A - geometry parameter of Gaussian distribution equal half diameter of laser beam, B - geometry parameters of Gaussian distribution equal depth of laser beam.

The radiation can be described with the Stefan-Boltzmann law and directional-, material- and surface-dependent emission coefficients for a "gray" body. But for the polishing process the emission coefficient of the quartz glass is stated with $\varepsilon = 0.91$ in [1] at T = 20 °C. The assumption in the simulation is that the emission coefficient is temperature-independent for the temperature range between 20°C and 3000°C.

The temperature-dependent material properties are from the literature and present the results of experimental investigations. The selected thermal properties for the quartz glass are from [2] for density, from [3] for specific heat capacity. The values of thermal conductivity may vary considerably, so a mean of two representative curves is determined [4], [5]. A heat input of P = 460 W and a diameter of beam A = 6.4 mm are for heat input model 1. The heat input and the feed-rate are depending on width for heat input model 2. But the beam has a constant velocity v_s=800 mm/s and the diameter of beam is 7 mm independent on with.

The numerical simulations are carried out with a parameter from the experiment for sample with 15 mm, 25 mm, 40 mm and 50 mm width. The aim of the process is generate a constant temperature of 2000°C on the sample surface in a line. The influence of heat capacity, density and thermal conductivity is presented in [6-10]. The results for the thermal and mechanical simulation for the heat input model 1 are presented and discussed in [9]. The results in [9] show that, for example, no clear correlation between changes in the preheat temperature and the maximum temperature is present.

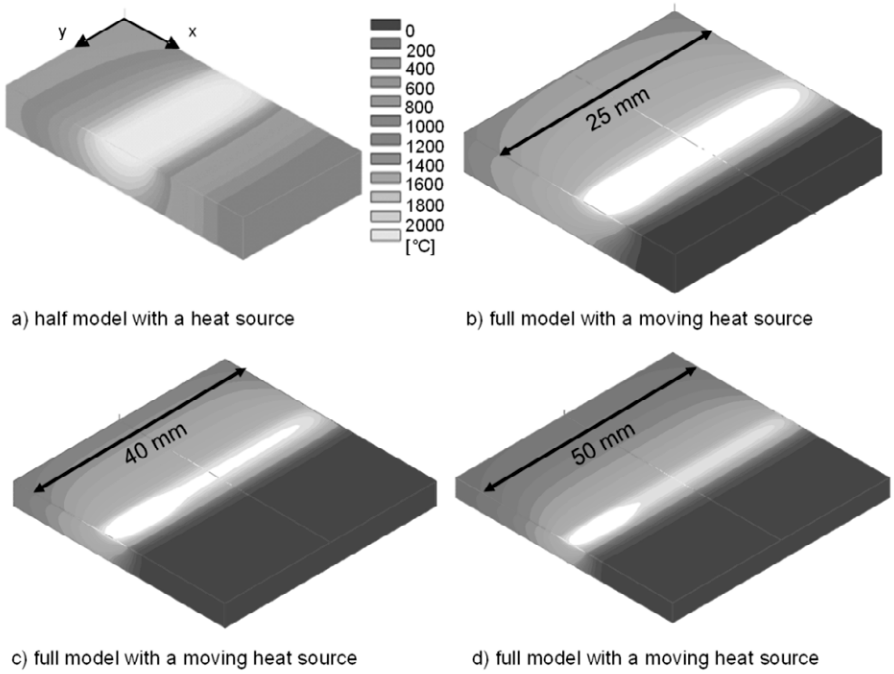


Fig. 4. temperature fields for different situations

With Fig. 4 it can be demonstrated that the description of the laser beam in the simulation can explain the significant temperature field and the temperature change during the polishing process. The calculation time for simulation with heat input model 1 is low, but the results are conservative and descriptions can be used for small sample. In the case of increase of sample width (Fig. 4 b, c, d) it is not possible to create a constant temperature in a line of sample surface. During the polishing process the sample get a heat treatment process. For small samples the effect of heat treatment process is not important, but in the case of complex samples a new concept for polishing process or temperature field must be developed.

A sensitivity analysis is performed for the thermal calculation for the sample with 15 mm width and the data from tab. 2. In the investigation following parameters are considered: the feed-rate, the beam velocity, the beam diameter and the beam intensity. The evaluation is realized for the maximum temperature for the measurement points in Fig. 5.

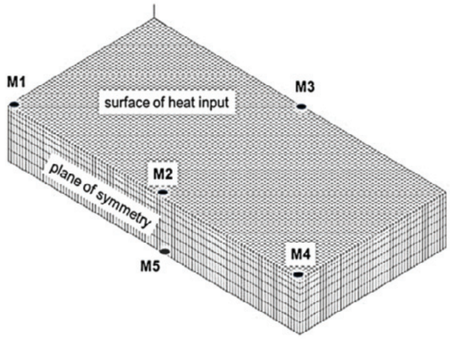


Fig. 5. position of measurement point

The Monte Carlo method is used to generate the stochastic input values with the mean and standard deviation. The standard deviation of 0.1 x mean is assumed because static data for the input values are missing. The selected results in Fig. 6 – 8 are depending on the position of measurement.

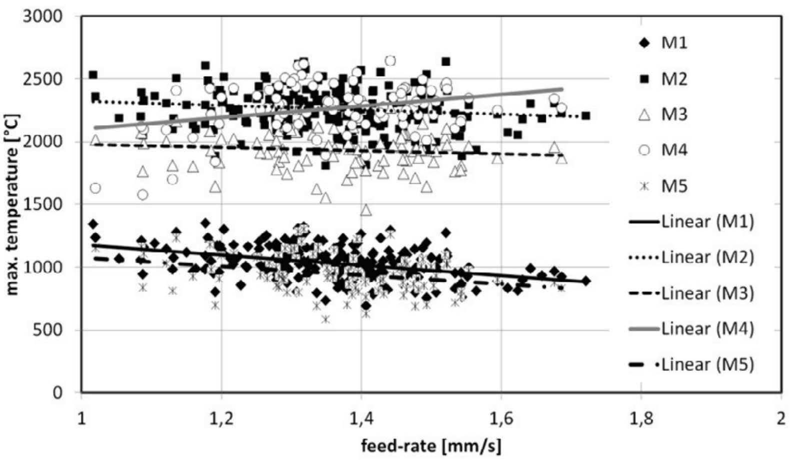


Fig. 6. results of sensitivity analysis - influence of feed-rate

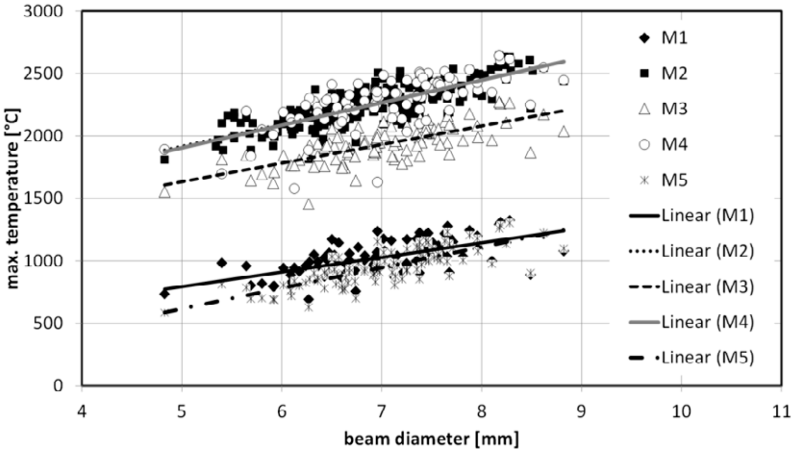


Fig. 7. results of sensitivity analysis - influence of beam diameter

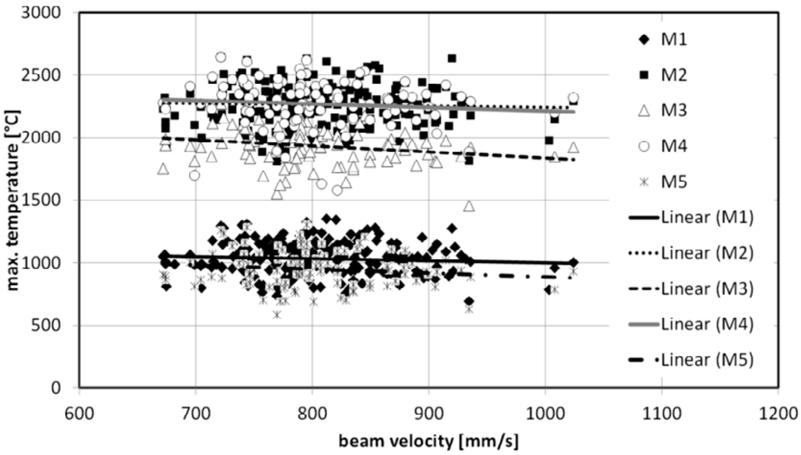


Fig. 8. results of sensitivity analysis - influence of beam velocity

The polishing process starts from measurement point M1 and ends in the measurement point M4. In all cases temperature in measurement point M1 is lower than in measurement point M4 and in measurement point M4 is the highest temperature. There is a heat loss in the sample at the beginning and a heat up at the end of process. For a uniform temperature on the surface of sample the laser would be moved more slowly at the beginning and faster at the end. With the numerical simulation the time points are determined for the change in feed-rate.

The results show that, for example, no clear correlation between changes in the beam velocity and the maximum temperature is present. Significant changes in maximum temperatures can be seen in the case of the beam diameter and beam intensity. This demonstrates that a critical examination of the input values is necessary.

Conclusion

Measurements on a stylus instrument (2D and 3D) show that laser beam polishing can reduce the initial roughness Ra from 0.2 … 0.8 µm down to 5 … 15 nm. Among other things it is indicated that the laser beam polishing technology does not change the surface contour however a suitable cooling process to reduce tensions may be necessary. Furthermore investigations with the SEM show that a very clean surface and polishing atmosphere is required to reach excellent surface quality. In contrast to the comparative mechanical finishing with a polishing rate of 228 s/cm² it is now possible to finish fused silica surfaces with 4.8 s/cm² by polishing with laser radiation.

The polishing process could be investigated by using the commercial FE-software SYSWELD for the calculation of the time- and location-dependent temperature distribution in the plate. The application of the laser-beam polishing process requires an extensive adaptation of the used material models. The application of simulation is suitable to optimization the process parameters of targeted temperature state.

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